Assessment of Existing Masonry Structures (The ARES project)

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Abstract

It is well established that in Europe, masonry is one of the most commonly used materials in construction due to its characteristics and construction simplicity. In addition, the majority of buildings that have any cultural and historical significance in Europe are built in masonry. Seeing that most of these masonry structures were built before the development of seismic regulations, many of them need to be evaluated and, if needed, strengthened. Today, standards and guidelines for the assessment of existing masonry structures do exist but are not very comprehensive and require a lot of engineering subjective judgment to implement. Furthermore, the energy renovation of existing buildings is one of the most pressing matters in the construction sector today, but structural aspects are somewhat ignored and/or disregarded. Since great financial resources are intended for energy renovation throughout Europe, it seems that structural updating and strengthening can and must be an added value for the energy renovation of buildings. This specifically applies to masonry structures, which in most cases need seismic strengthening. The assessment techniques focus mainly on damage identification, damage localization and damage evaluation as well as determination of certain material properties of existing structures. The diagnoses are based on the design procedures of new structures and the planning of interventions often suggests reinforcement. The current practice of the assessment of existing structures might not be considered suitable to facilitate confident decisions about the reliability of structures. The main objective of the ARES project, partially presented in this article, is to study the role of assessment on the reliability analysis of existing structures.

1 Introduction

According to various literature and recent events, it is certain that masonry is one of the most commonly used materials across the world, due to its construction simplicity and characteristics. Despite the fact that the use of masonry as a building material in earthquake-prone regions pointed out its limitations (limited tensile resistance, relevant mass and stiffness), extensive research has been carried out in the last few decades mainly focusing on the material characteristics and structural behaviour of masonry, even under extreme loads such as earthquakes. These efforts enabled engineers to design masonry structures on sound and safe principles, with greater exactitude, economy and confidence. If it is taken into account that most of the buildings with high cultural significance and historical importance are built in masonry, it is quite clear that the assessment and rehabilitation of existing masonry structures must be conducted on a very high level.

The main goal of a seismic design is to protect property and lives in buildings in case of earthquake events. However, a proper seismic design should be developed on the knowledge gathered from existing structures. Past events have showed that seismic loads cause significant damage to masonry buildings due to their large mass and stiffness. Given that a great number of people across the world live and work in masonry buildings this represents a great risk. Furthermore, a huge number of these buildings were built before the development of seismic codes, so no confining or reinforcing elements exist. Based on all of the above, a concise strategy for masonry buildings must be activated.

The seismic behaviour of buildings depends on several important factors such as material properties, the geometry of a structure, stiffness properties and many more. Thus, the issue of seismic vulnerability of underperforming existing masonry structures is very complex [1]. “Seismic vulnerability” can be conventionally defined as a measure of the inadequacy of a given structure to resist to seismic actions [2]. Modern methods for the assessment of seismic vulnerability are represented by design curves which express the physical vulnerability as a function of the intensity of the process and the degree of loss [3]. However, when it comes to masonry, seismic vulnerability is quite difficult to assess and it requires a number of specialized technical skills [4]. But are these methods in use applicable to the assessment of existing masonry buildings?

This question remains unanswered since extensive research needs to be carried out on the topics of seismic risk and vulnerability assessment. Traditional assessment methods, in most cases, are well-known to allow the assessment of only the actual condition of a given existing structure, once its stability has already been compromised. In this paper, assessment methods of critical properties (structural and material parameters) are presented for masonry structures. A focus is set on the available methods able to provide crucial data and feedback for preventing failure mechanisms and collapses under extreme design loads.

2 The Croatian Résumé

Approximately 75 % of Croatia's building stock is older than 30 years, an age requiring renovation/modification of primary structural components. More than 40 % is older than 50 years, meaning that the service life of these buildings has expired. Finally, in the building sector in Croatia, 40 % of the expenses are assigned to the demolition or rehabilitation of existing structures (Fig. 1 (left)) [5].

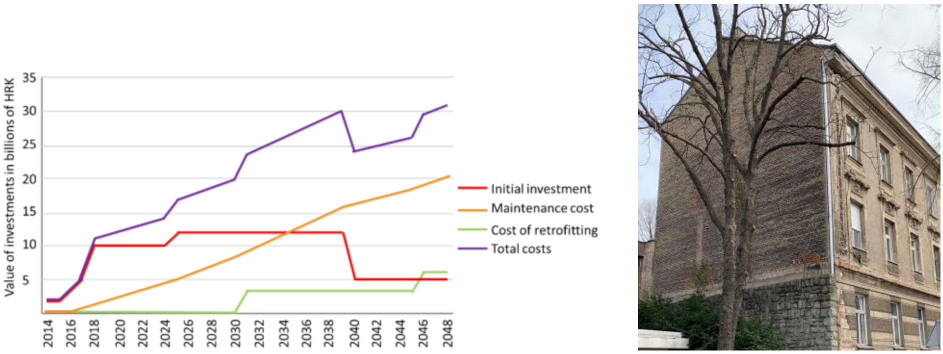

Fig. 1 (left) Investment (HRK) for the renovation of Croatian national building stock [5]; (right) Typical masonry building in Zagreb (photo by I. Hafner).

Most of Croatian buildings constructed in the period before the 1970s, when the seismic codes were introduced to the civil engineering community, were built using traditional construction materials such as masonry and timber (Fig. 1 (right)). Buildings were built as full-brick masonry structures with 30-60 cm thick walls and wooden ceilings. Unfortunately, it is recognized that in Croatia the majority of residential buildings older than 50 years are masonry structures without adequate bonding elements connecting the floors and the walls [6].

3 Maintenance issues of existing masonry structures

Existing structures can be divided into two groups regarding their value. Some buildings have a higher economical value like most of the modern buildings that exist today, and some buildings have a more non-material value like heritage structures (cultural and historical buildings).

Accordingly, the assessment of existing structures can be performed in different steps with a different level of precision. The level of precision depends on the importance of the building assessed and can be achieved by breaking down the assessment into phases. The number of these phases is dependent on a number of factors like the remaining level of doubt, simplicity and/or feasibility of repair etc. taking into account the economic aspects [7].

When it comes to masonry structures per se, a variety of assessment methods do exist, but their frequency and scope, the decision-making process and the necessary interventions are not yet agreed upon. The need for an assessment of an existing structure can come from a number of reasons [7]. Besides that, there may be situations where questions are raised regarding the design assumptions of a building. In the following scenarios a re-assessment of a structure might be necessary [8]: extended service life, change in utilization, required increase in the level of reliability, lack of maintenance and inspection, inadequate serviceability, exposure to extreme loads, availability of new knowledge gathered from negative experience from similar structures and revised design codes etc.

4 Assessment methods

Masonry structures are composite systems made from masonry units that are connected by mortar layers. Both can be made of different materials with different characteristics. Besides the type of the material used, the overall mechanical behaviour can be affected by a number of factors such as geometry of masonry units (length, width, height, volume of holes etc.), the thickness of mortar and the area it covers. For the assessment of masonry structures specifications of compressive strength are often required. Assessing the variability of these properties and the uncertainty in the modelling of the masonry compressive strength is hence a topic of great importance [9].

When it comes to existing structures the problem lies in the uncertainty of the strength classes of the materials used. Therefore, the assessment methods used should aim at identifying these properties with the highest degree of certainty so that the uncertainty regarding the resistance of a structure in whole is reduced to a minimum.

Parameters that are always measured during the assessment of a masonry structure are (a) the compressive strength of masonry units, (b) the compressive strength of masonry mortar, (c) the compressive strength of concrete infill (if any), (d) the strength of reinforcing steel bars (if any), (e) the compressive, shear and flexural strength of masonry, (f) the Modulus of Elasticity (MoE) and the geometry of the masonry structure (size and location of bearing walls, location and size of openings).

For obtaining these parameters several NDT (Non-Destructive Testing) methods are used and summarized in Table 1 and Figure 2.

Table 1 Available Non-Destructive Testing (NDT) assessment methods for existing masonry structures.

NDT Method	Device	What Is Measured?	How Is It Measured?	References
Visual inspection	/	Quality of masonry (mechanical parameters, dimension, shape), mortar and wall connections	Without a device, using a base/set of rules (i.e., Masonry quality index-MQI)	Borri et al. [10]
Measurement of reinforcement location	Ground Penetrating Radar (GPR)	Location (depth) of reinforcement	The device is placed on the measured surface and moved along a linear axis (with a calibration needed), transmitting radio wave signals into a structure and detecting echoes	Agred, Klysz and Balayssac [11]
Measurement of masonry unit hardness	Rebound hammer (Schmidt hammer)	Compressive strength of masonry units, mortars and built masonry	A predefined number of tests is conducted in both horizontal and vertical direction (with a calibration needed)	Breysse et al. [11], Sýkora et al. [12]
Stress wave transmission	Ultrasonic Pulse Velocity test (UPV) test/Resonant frequency test (RF)	Compressive strength of concrete or masonry	UPV-two transducers are placed on two sides of the specimen after which the time of wave travel is measured RF-a piezometric sensor is used with different attachment techniques to obtain resonant frequency	Sajid et al. [12]
Ultrasonic velocity testing	Impact hammer and accelerometer	Characterization of masonry wall homogeneity and variability	On opposite sides of the wall, an impact hammer and an accelerometer are placed. The mechanical impulse is generated by the hammer striking the material and the signal is	Mesquita et al. [13]

			then received by the accelerometer.	
Sonic velocity testing	Impact hammer and accelerometer	Location of heterogeneities, voids or inclusions of other materials in masonry elements	On opposite sides of the wall, an impact hammer and an accelerometer are placed, after which the mechanical impulse is generated by the hammer striking the material and the signal is then received by the accelerometer	Martini et al. [14] Valluzzi et al. [15]
Surface penetrating radar	Ground Penetrating Radar (GPR)	Location (depth) of reinforcement, thickness of elements, position of voids and moisture content	The device is placed on the measured surface and moved along a linear axis (with a calibration needed) transmitting radio wave signals into a structure and detecting echoes	Martini et al. [14] Wai-Lok Lai, Dérobert and Annan [16]
Infrared thermography	Thermography cameras Visual IR thermometers	Defects in the building's envelope, the monitoring of reinforcing steel in concrete, the detection of moisture etc.	The specimen is under thermal stimulation and its surface temperature variation is monitored during the heating or cooling phase (the presence of inhomogeneity in a material causes local temperature variations)	Meola [17]
Borescope and mortar hardness with pendulum rebound hammer	Borescope and pendulum rebound hammer	Borescope-anomalies and internal wall components, such as ties, flashing and drainage cavities Pendulum rebound hammer-mortar type and strength	The borescope is inserted into small holes drilled into mortar joints (with fiber optics and internal light source) The pendulum rebound hammer utilizes a low energy impact and the resulting rebound from the surface of a mortar joint is used to measure surface hardness	Schuller [18]
Flat-jack tests	Flat jacks	Deformability parameters in compression, compressive strength and shear strength parameters	Two cuts are made with a predefined distance between them (horizontal cuts for compression, vertical cuts for shear), after which the jack is inflated with a liquid that transmits hydrostatic pressure	Parivallal et al. [19], Simões et al. [20],
Acoustic emission		The damage evolution in masonry, evaluation of the reliability of reinforcing techniques, analysis of residual capacity of masonry	A group of transducers are set to record signals, then locate the precise area of their origin by measuring the time for the sound to reach different transducers.	Invernizzi et al. [21]

Fig. 2 (left) Ground penetrating radar [14]; (middle) Pendulum rebound hammer [22]; (right) The flat jack test [23]

Supplementary to the assessment methods, a continuous Structural Health Monitoring (SHM) system might be of great use for a better understanding of the actual behaviour of a given structure. Since this way of monitoring a structure is quite useful, it should be seen as a goal to enhance the benefit of SHM by the utilization of applied decision analysis on how to assess the value of SHM even before it is implemented. By using SHM techniques the decision-making basis for the design, operation and life-cycle management can be much improved and can facilitate more cost-efficient and reliable strategies for maintaining and developing the built society [24].

5 The ARES Project

Maintenance of the building stock today is not only an issue that concerns the civil engineering community, but it is also an environmental, social and resource efficiency issue that should concern the general public.

The wide range of assessment methods presented in the previous paragraph shows that a big step forward has been taken in this field in recent years, but this has not yet changed the quality of assessment in regard to the evaluation of the reliability of an entire structure. Since most methods focus on the determination of local properties and damages that do not represent the properties and the capacity of an entire structure it is obvious why these methods are considered insufficient. Advanced methods for the assessment of existing structures make use of updated information but unfortunately that is not quite the case with masonry structures [25]–[27].

At this moment the assessment methods and the design checks of existing structures are not at the same level. Without high quality guidelines it is difficult to approach a problem which consequently results in a false interpretation of collected data and a wrong decision-making process for the rehabilitation of an existing structure. The development of investigation techniques for the updating of material properties will help with the uncertainties associated with the prediction of the structural behaviour of existing structures.

The ARES project, funded by the Croatian Science Foundation, was established with the idea of ironing out the mentioned insufficiencies. The aim is to deliver a basis for the advanced assessment and the design of existing structures, allowing a more economic design and a more accurate analysis of the consequence of failure. To sum it up, the idea is to improve the way assessment is carried out. Standard methods will be compared, and the necessary procedures will be determined to simplify assessment for practical use. Furthermore, it is aspired to develop general guidelines, to review the safety factors in place and to gather great knowledge about the building stock in Croatia in general. With the knowledge gained in this project, Croatian society of engineers will have an opportunity to actively participate in the research and will contribute (via National Standardization Committee) to a production of a new standard.

6 Conclusion

The Croatian and the European building stock consist of many masonry structures that are vulnerable to seismic activities. To reduce this vulnerability, they are strengthened with mostly steel and sometimes non-metallic reinforcement after the assessment is performed. Since sustainability is becoming a prevailing issue, the general aim seems to be shifting from building new structures to the maintenance of existing ones. That is why the assessment of structural behaviour and strengthening techniques are becoming a hot topic in the civil engineering society. However, many questions regarding seismic vulnerability and the assessment of masonry structures remain unanswered even with the tools and techniques that are already at disposal. One of the main issues lies in the fact that most of the historic and a great amount of residential buildings are built with masonry, so both the economic and cultural aspect are at risk. Also, in most cases the access to the interior of a building is not even possible so the array of assessment methods and retrofitting techniques decreases significantly. Furthermore, on a more global scale, energy efficiency is currently being improved in a lot of structures without any seismic or even structural considerations. Some simple solutions may lead to a large improvement in seismic behaviour, such as adding horizontal steel rods to ensure a box-type behaviour of a structure.

Most of the existing rules and standards regulate the design of new structures but the maintenance and if needed repair are not elaborated that well. Some guidelines and documents do exist, but they need to be improved. That is why further research about material properties and their variability, risk assessment and modelling are needed. Currently, there is a huge knowledge gap, especially in the assessment methods and design checks for existing structures, in every aspect of the assessment process.

First of all, it is very important to define which parameters need to be tested and which can be calculated or approximated (i.e. Is it necessary to measure mortar characteristics or are they similar for the Croatian building stock?). The plan of the project is to make case studies on existing masonry structures to form an exact procedure. Secondly, the idea is to find an economic approach for modelling such a series of structures since the current practice is usually either to complex or to simple. This will be achieved by modelling a structure with various input data and afterwards trying to assess the structure before the testing. The values will be compared to the ones provided by tests and models will be calibrated. This procedure will be repeated until a reliable system will be obtained. Thirdly, gaps exist in the way strengthening is ensured (which safety factors can be expected for a specific strengthening technique, masonry and standard practice characteristic of Croatia? How does strengthening influence the parameters for modelling? etc.).

The ARES project tries to address these shortcomings, allowing for a more economic design and a more accurate analysis of the consequences of failure.

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